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(6) HARDMAN Life Cycle Cost Methods: Recommendations

by

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1.0 INTRODUCTION

This report represents the culmination of more than two years of research on the use of life cycle cost analysis in the acquisition process. The specific concern of the study has been the ability to perform cost tradeoff analysis to find feasible least cost mixes of capital and labor. A collateral goal has been the development of methods capable of performing such analysis under conditions of limited information such as the earliest stages of design. Accordingly, the work has resulted in two types of developments. First, new formulations for the estimation of manpower costs have been developed and partially tested. Second, a new structure for cost model systems has also been developed and tested.

The purpose of this report is to present recommendations, based on this research, for the kinds of models and model systems the Navy should develop to support the acqusition process. A brief review of the reasons for the recommendations is presented here, but the reader is referred to earlier work for detailed rationale.*

* Five reports make up the bulk of the work. These are Neches, T. and R. Butler, "Guidelines for Hardware/Manpower Cost Analysis," AG-PR-A100-2 (3 Volumes), 1978; Neches, T., and R. Butler, "Demonstration Model System," AG-PR-A101 (5 Volumes), 1979; Neches, T., C. Low and S. Simpson, "A Review of Current Manpower and Cost Estimation Methodologies," AG-PR-A103, 1979; Neches, T., C. Low and S. Simpson, "A Survey of Navy Cost Model Input Variables and their Data Sources," AG-PR-A104, 1980; Butler, R. and S. Cylke, "Civilian Billet Cost Model," AG-PR-A102, 1979. In addition, see Neches, T., "The Demonstration Model System: An Overview," AG-PM-A104-1, 1979 and Butler, R., "The Use of Life Cycle Cost Analysis in Hardware Design," AG-RD-120, Military Operation Research Society, 44th Symposium, Vandenburg AFB, 1979.

Throughout the research effort, the model system used to study various aspects of the problem has been tailored to shipboard electronics systems. One of the questions that must be answered, therefore, is what equipment types and operating environments must be modeled separately. Different, but related problems have to do with the number of maintenance echelons and equipment indenture levels that must be modeled--and whether these questions are related to deployment environment or equipment type.

At another level, should the idea of linked and graded models be used? If so, precisely what gradations are appropriate and do these differ for diverse equipment types. Are general purpose models feasible at all, or must new models be developed for each specific system? Can multi-environment models be created by ganging single environment models, or are more complex adjustments necessary?* Are modular models possible, in which the specifics of a particular environment/equipment combination can be modeled by the assembly of several standard modules? If so, how are these modules defined and implemented?

The questions suggested above are structural in nature. Their answers will determine how many models of what types will ultimately be developed by the Navy for use in the acquisition process. Another range of questions has to do with the algorithmic content of the models. The broadest of these questions--the use of paramet-

* A multi-environment model is required for systems that operate in more than a single environment, e.g., a laser communications system, such as SAOCS, linking surface ships and land bases via aircraft.

rics versus process formulations--may be of little import. Certainly there are instances where each is appropriate. This leads to the conclusion that some hybrid form will be the most useful, but the selection of the best ways to use each remains as an important question.

Innovations in the estimation of manpower requirements (and hence costs) and spare stockage costs have been introduced by the prototype models. These formulations, while logical, are untested. Their retention in the final models must therefore depend on the results of pilot programs in which reasonably intensive testing can be carried out.

Another significant and very general question is suggested by consideration of these two areas: should cost models be based on optimality conditions or should they attempt to reflect the reality created by actual policies used in the Navy?* The latter, far more realistic and extremely demanding, would also allow cost analysis of the policies themselves--rather than simply cost analysis of hardware systems given the policy environment. The virtues of the former are its ease and conventionality: users understand cost models to be based on optimality conditions and make implicit adjustments predicated on this expectation.

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* For example, it was Navy practice some years ago to determine "optimal" stockage levels using complex models--and then to purchase 85% of the amount determined. Intended as a means of reducing spares cost by 15%, there is evidence for some systems that it ultimately <u>increased</u> spares cost, because of behavioral responses to insufficient stockage. Modeling these responses to estimate the real cost impact of inappropriate policy is what we mean by modeling reality. Alternatively, optimality conditions answer the quesion, how many spares <u>should</u> the Navy buy.

The issues introduced above are discussed at length in the following pages. We have attempted to draw reasonable conclusions and base our recommendations on these conclusions. The criterion for reasonableness is the one which underlies, not only the discussion here, but virtually everything written in the reports cited earlier: cost effectiveness. We have recommended a set of model systems predicated on our judgement about the utility of a given characteristic compared to its cost--either in development or in use by participants in the weapon system acquisition process.

2.0 STRUCTURE OF MODEL SYSTEMS

The two major questions regarding the kinds of models appropriate for HARDMAN objectives are related to form or structure and content. This section deals with the first. During the course of research on cost analysis for HARDMAN objectives, three structural issues have arisen. First, the idea of linked and graded models, while intuitively pleasing in a laboratory environment, may present difficulties in execution. Second, as we think more concretely about what kinds of models are needed (i.e., electronic vs. mechanical or sea vs. land) it becomes clear that a prodigious number will be required. Third, because of similarities in the general structure and common elements in many of the model types required, the idea of modular cost model components has sufficient appeal to be explored. These three issues are discussed in the subsections below.

2.1 LINKED AND GRADED MODEL SYSTEMS

The general idea of linked and graded model systems was introduced in the Guidelines study and explored further with the Demonstration Model System.* Gradation of the detail and attempted accuracy of cost models was suggested as a means of addressing the conflict between lack of information at the earliest stages of design coupled with the profound impact of early design decisions

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* op. cit. A100 and A101

on ultimate life cycle cost. Existing models generally require more data than can be generated in this critical early period. Thus the major contribution of graded models is the introduction of simple ones to provide some information as opposed to nothing at all. At higher gradations (i.e., more complex models), this argument is no longer germane, of course. But, at intermediate stages of design many models demand too much or too detailed information. We have observed many design programs, as a result, in which a mandate from the government to use a particular, detailed, model has driven parts of the design to a too-hasty conclusion. That is, the cost analysis requirement has been allowed to drive the engineering design, rather than augment it. By introducing an intermediate level of models, the grading system allows design to proceed at a natural pace, providing it with appropriately detailed cost analysis during the period when, although much information is available, many aspects of the design are still in flux.

Linkage of cost models follows as a logical requirement from using different grades of detail, and therefore different models, in the course of a single design effort. The objective of achieving linkage is to keep, as far as possible, a consistent set of decison criteria. This can only be done by achieving mathematical consistency between the models: the algorithms of each model level must be essentially the same with assumptions replacing data in the simpler versions. Inconsistent algorithms actually take substantively different approaches to the estimation of the same thing and can therefore lead to inconsistent conclusions, given the same data.

Existing models provide an example of mathematical inconsistency in the estimation of spares cost. The Air Force model, MOD-METRIC,* is among the most sophisticated spares models in use. It performs marginal allocation of funds to the single item of stock which decreases expected base level backorders at the most advantageous rate of cost for effect. This would be analogous to what we intend for Level III models. To do this type of computation requires a machine which can operate on data representing all of the elements of a system simultaneously. At the other end of the scale (analogous to what we intend for Level I models) are sparing algorithms typical of sequential process models such as the Air Force LSCM and the Navy's 1390B models.** These models (but not the DMS Level I models) ignore cost criteria as well as system effectiveness criteria: they buy spares to a stockout criterion which is independent of the system. They do this, presumably, because they are meant to consider one component at a time, thus requiring far less computational power to run.

The middle ground between the two extremes mentioned (analogous to what we intend for Level II) is occupied by a wide variety of

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* See, Muckstadt, J., "A Model for a Multi-item, Multi-echelon, Multi-indenture Inventory System," Management Science, Vol. 20, No. 4, December, 1973. By definition, a backorder exists when there is an unsatisfied demand at base level.

** See, "Logistics Support Cost Model User's Handbook," AFALD/XRSC, Wright-Patterson AFB, 1979 and Mil-Std-1390B, Military Standard Level of Repair, Department of the Navy, Washington, D.C., 1976.

models, none of which is representative. For our purpose, imagine a model which purchased spares to a system level effectiveness criterion, but not in the context of cost minimization. Inconsistent formulations such as the three just mentioned can lead to widely different estimates.

A hypothetical system is easily constructed which at Level I would require no spares, at Level II, $20 million worth and at Level III, perhaps $15 million.* If such a system were designed with the "help" of these inconsistent estimates, one can imagine that the designer would soon become disenchanted with the whole idea of cost modeling. If the design was predicated on the results of these models, it would be far more costly than necessary.

A set of mathematically consistent models would introduce both cost and system effectiveness criteria at Level I, despite the need to process components sequentially. This is easily done by developing a confidence level criterion which is a function of both the individual characteristics of the component and the aggregate characteristics of the system. A device of this type is explained in detail in the Demonstration Model System (Vol.

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* These values are based on 200 systems, operating in 200 different locations, each with 100 components with the same failure rate. The failure rate is just sufficient to yield a demand during lead time of .05. Therefore, a (Level I) sequential processor using (as is typical) a criterion of 95% confidence against stockout would buy no spares. Another model (Level II) which considered the whole system at a confidence level of 95% (again, typical) would buy one spare of each type for each of 200 locations. At a price of $1000 each, this amounts to $20 million. If there is a reasonable variance among the unit costs of the 100 part types, the use of an economic criterion (in a Level III model) would reduce the cost to, perhaps $15 million.

I). That system would yield a spares cost estimate of roughly $15 million at all three levels.

The DMS showed that linked and graded model systems can be developed. In particular, reasonable linkage can be created by careful formulation of the algorithms used in the lower level models. But the degree of detail in each level is still a question.

The terminology created to portray gradations was originally machine-determined. That is, Level I models were originally conceived as those which would fit on programmable calculators, Level II meant self-contained micro computers and Level III required main-frame machines. But as the capacity of calculators and micro computers grows, these distinctions have become somewhat blurred. Even so, the appropriate level of detail in the model levels is relatively easy to specify. The Level I models must be usable when no more than five or ten variables can be estimated to portray a particular component. The Level III models must be capable of accepting and exploiting every datum characterizing even the smallest nuances of a full system design. Level II models should be as detailed as possible, given that they must process system components sequentially rather than simultaneously. These distinctions are dealt with at greater length below.

2.2 EQUIPMENT TYPES AND OPERATING ENVIRONMENTS

The Navy procures a staggering variety of equipments for use in four dissimilar environments: land, sea, air and space. The operating environment which must be characterized by the operating and support (O&S) component of a life cycle cost model depends not only on the medium (land, sea, etc.), but also on the platform class and sometimes the mission. The variety of possibilities is made explicit by the following list:

Land:	Operational Administrative
Sea:	CV Other surface Submarine
Air:	CV NAS
Space:	Land Space

The equipments themselves can be divided into three broad classes--electrical/electronic, mechanical and structural. Virtually all equipments include some mix of all three. Strange as it may seem, most of the progress made to date in life cycle cost analysis has addressed only electronics. Very little is known about failure mechanisms and how to portray them for mechanical or structural items. A similar situation exists with an item not even included in the list--software. It is known that a larger and larger proportion of system acquisition costs are devoted to software development. It is less well known but becoming obvious that software O&S costs are also becoming significant. We leave the latter aside for the moment. However, the large and growing costs of maintaining software (almost exclusively manpower costs) may well lead to concern on that score at some time in the future.

The simplest way to determine how many models are required to cover all the Navy's systems is to multiply the number of operating environments (9) by the number of equipment types (3) by the number of model levels (3). This gives the staggering total of 81 different models. If one further considers that most Level I models are usually model systems containing at least three individual programs, this total rises to 135. The time and expense involved in developing so many models is clearly unwarranted if alternatives are available.

One approach is to cut down the list as much as possible by determining which operating environments, while different, can be modeled with the same algorithms. For example, submarines and other surface craft can be modeled in the same way with the differences being portrayed by parameters rather than model structure. The scope of such combinations is limited, however, if an entire model is taken as the unit of account. The feasible extent of such combinations seems to be to cut the list roughly in half--which would still require about 65 models.

Another approach is to separate the models into their components: development, production and the elements of O&S cost such as spares, training, technical data and so on. For each of these segments there is considerable commonality. For example, development and production costs will use roughly similar algorithms irrespective of operating environment. Spare stockage requires no more than four different formulations to cover the 27 equipment/environment combinations. Technical data costs and inventory entry and management costs will only require single algorithms for all the model types. Perhaps three or four algorithms will be required to estimate manning for the variety of environment types. At each model level, therefore, it may be necessary to build no more than the equivalent of two or three full cost models by separating the cost elements and treating each as a building block for a specific equipment/environment combination. There are some problems involved in doing so, however. These are discussed in the next sub-section.

None of the foregoing discussion has mentioned the problems associated with multi-environment systems. At Levels II and III these problems are probably tractable since more than one model can be used and the results aggregated easily. At Level I, however, no simple solution has, as yet, suggested itself. The appropriate resolution of the question will have to await a pilot case before alternative methods can be explored.*

2.3 MODULAR COST MODELS

Development of a system of cost element modules from which a wide variety of special purpose models could be constructed has

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* We have developed one multi-environment Level I model system to date--the Navy Command and Control System cost model. This model used separate data sets for land and sea deployment. But it was a very difficult, special purpose model system and seems inappropriate as a prototype for the HARDMAN models.

both advantages and disadvantages. The major advantage is cost savings, as noted above. The disadvantages have to do with the difficulty of developing general structures which will serve for a wide variety of specific cases.

In addition to the decision whether to take a modular approach to model development, an additional question is whether the result should be put into use as a modular system. While development costs can be saved through modularity, it seems reasonable that the final product should appear to the user as a special purpose model system.

Development

While development of a modular system is inherently less costly than a very large number of specific models, each part of a modular system is more difficult to implement. The main difficulty is to insure that a module is compatible with all the uses to which it will be put.

Compatibility must be achieved both in the mathematics used for a particular cost element and in the computer code by which the algorithms are implemented. For example, there are normally two demand rates used in O&S cost elements: average annual demand and demands during a peak period. The latter is generally defined as a deployment period for a combat system, whereas the period is arbitrary for a land-based operational system. Moreover, a land-based administrative system may not use peak demands at all.

An algorithm for the number of maintenance specialists to be trained may be the same for all three environments except that the dimension of a variable for demand will be different. All such problems must be foreseen and accomodated to develop a modular system.

To insure that the algorithms operate correctly requires a great deal of care in planning the detailed specifications of the entire system before any single system is actually developed. Since planning computer code (especially with limited memory devices like calculators) is an inexact process, the implied degree of foresight is usually impossible to achieve. In operational terms, this means that a comprehensive plan will require continual updating as each module is actually implemented in real code.

The modular approach also requires that a standardized model structure be developed, whether it is actually implemented or not. The general structure performs house-keeping functions, establishes and controls the operating sequence, acquires data from storage media and passes it to the blocks of code which use it and so on. In a system which was modular from the user's point of view a standard structure would actually have to be developed. Modules would then be selected to cover each cost element appropriate to a given equipment/environment. In a model system which appeared to be special purpose to the user, the standardized structure would not have to be implemented except as guidance for each specific structure. The latter course is clearly less demanding while it also implies the need for a larger volume of computer code.

Use

The two basic approaches to the use of modular models are more easily distinguished when compared from the user's point of view. True modular code requires the user to select and assemble the series of modules required by his specific problem. Special purpose models (whether developed under a modular discipline or as special purpose models) do not.

The need to assemble modules has three effects. First it imposes a cost, both in resources and time on the user. Second, it is an error-prone process, allowing a user to make inappropriate selections. Third, however, it also makes it unnecessary to anticipate every specific problem beforehand. That is, if a problem arises that was not anticipated, true modularity allows a user to formulate the most appropriate model system available through the full range of modules.

We believe it is feasible to take advantage of the flexibility inherent in a true modular system while avoiding its problems by making the models appear to be special purpose from the user's standpoint. It would be necessary for the HARDMAN Development Office to remain prepared to assemble a new special-purpose system from time to time, as unforeseen requirements arise. Occasional updating would be required as well. While this would normally be a very costly process, it need not be if development is based on a modular approach. Any new requirement would normally be satisfied by assembling existing modules or, at worst, adding one or two new ones to the entire collections. Even "new" modules would rarely be completely new. More than likely they would amount to minor modifications of existing code.

3.0 MODELING QUESTIONS

No matter how efficiently cost models are built, or how cleverly they are presented, they should also be capable of accurate cost estimation. But while this desire for accuracy has been a touchstone of the cost analyst, we believe it may have been pursued, in some cases, to the detriment of efficacy. The most accurate cost model in the world is a useless artifact if it is not employed for cost analysis. The structural questions raised in Section 2 were largely concerned with how to develop a useful cost model system.

This section explores three major areas having to do with the accuracy of cost algorithms. One area--manpower--is of obvious interest because of the goals of the HARDMAN Development Office. Beyond this, however, manpower is an important area because of the general lack of accuracy with which its associated costs have been estimated by most extant models. Another specific area treated below is spares cost. Here the focus of attention is the tremendous variation in estimates yielded by the variety of existing models--and the possibility of bringing early and late estimates closer together. The third area dealt with is a more general question which potentially impacts the estimation of all cost elements: should cost models portray optimal or real environments?

There are several areas of cost analysis not addressed here. For example, a wide variety of techniques is currently employed for the estimation of support and test equipment costs. These costs are undeniably important and the variety of methods produce very large differences in cost estimates. Nonetheless, they are not treated here simply because, at this point, we have little to add to the field. Other cost elements, like transportation, can be modeled with great complexity, but their importance is so small that they are also ignored. Neither of these is the case with either manpower or spares cost estimation.

3.1 MANPOWER COST ESTIMATION

Manpower costs include those directly associated with the retention of a man in the service, which we (imprecisely) call compensation costs, those associated with job-specific training and a number of other, indirect costs. In the algorithms developed for HARDMAN, compensation costs depend only on, among other things, the number of hours of labor actually consumed by a given hardware system. To estimate training costs, however, the algorithms first establish how many people (i.e., integer numbers of people) must be trained. Among the various indirect costs some, such as security clearance costs, depend on integer numbers of people while others, such as management and administrative costs, depend on the amount of a man's time actually used by the system.

The central mechanism used in the manning algorithms distinguishes three groups of manpower in a ship environment: men available with the appropriate "A" school background for the skill needed; men available with no appropriate school background, but capable of passing both "A" and "C" school courses of instruction; and men in general manpower pools not currently assigned to the ship. These groups are called the AN, AG and AS manpower pools, in ascending order of cost to prepare for duty. Members of the AN pool need only "C" school training while those from the AG and AS pools also need "A" school training to equip them for duty with the new system. People drawn from the AS pool may also need other kinds of training and give rise to other costs because they add to the ship's company.

The algorithms are driven by the size of the AN and AG pools, filling the new manhour requirement as economically as possible. While conceptually reasonable (in fact a faithful portrayal of the way in which ships satisfy the need for new specialists) the algorithms impose data problems on the model user which may be impossible to overcome.* Conversations with experienced officers from the fleet have provided a variety of statements concerning the availability of underutilized personnel. Most seem to agree that the force is overloaded with work already, but many agree much of this work could either be foregone entirely or performed in far more efficient ways (i.e., labor substitution opportunities abound at very favorable rates of exchange).

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* See the discussions of AG and AN in op. cit. A104, Appendix A.

As the algorithms are currently formulated, the AS pool (shore personnel) are treated as lacking the appropriate A school background. If the available manpower on board is as restricted as testimony--though not data--indicates, then far more attention will be focused on the AS group than was intended. At a minimum, this would imply the need to split the shore pool into groups with and without the appropriate "A" school.*

Note that these questions are only pertinent with regard to training costs and others which require an integer number of personnel to drive them. Compensation costs are based on the notion of opportunity cost: whether a man is really available (i.e., underutilized) does not matter since one of the elements of his compensation costs associated with the new system is his foregone output in the alternative use. Thus, if the job he used to do is simply not performed any longer, the foregone benefit is registered as a portion of the cost of his performing the new work. The budget cost arising from such a shift can either be equal to or greater than the cost charged to the new system, depending on whether the Navy gets along without his former output or replaces it by adding more labor. In either case, the real cost created by the new system is the same.

As with some of the other questions raised here, the significance of the data issue can only be tested by an attempt to employ

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* This idea arose in a conversation with Dr. Mike Sovereign of the Naval Post Graduate School, whom I would like to thank for this and several other comments.

the algorithms with a pilot program. Alternative formulations can then be explored if data collection appears infeasible.

3.2 SPARE STOCKAGE COST ESTIMATION

The spare stockage algorithms introduced in the DMS for Level I and II models are distinguished by three features. First, the number of spares are sensitive to geographic location, making it impossible to place, for example, .1 spares on each of 10 ships. Second, the effectiveness criterion employed allows each component to be spared with respect to its relative cost and its contribution to the system's failure rate. This is done despite the need for sequential processing of each component due to limited machine capacity. Third, the spares solutions are linked to recurring unit production cost. That is, the average unit cost declines through a learning curve formulation as numbers of spares increase, possibly altering the confidence criterion to which spares are procured and, in any case, changing the total cost of spares and production of the system.

Because the algorithms used for sequential processing employ the techniques described above, they are able to simulate solutions formerly obtainable only with large machines which allowed simultaneous consideration of all system components. As a result, the spare stockage solution obtainable by aggregating Level I model solutions early in the design process should not differ markedly from those obtainable at the end of the development process--except as a result of data refinement.

The algorithms used in the DMS are based on a Poisson arrival distribution or a normal approximation, implying a (stationary) exponential failure mechanism for electronic components. While much evidence is available to indicate that these probability distributions are appropriate, evidence also exists to the contrary. We prefer to make no judgment about the relative virtues of this or that distribution. The methods outlined for simulating simultaneous solutions on sequential processors will hold, no matter what distributions are used. These methods are recommended for use by HARDMAN in the development of new model systems.

3.3 MODELING REALITY VERSUS OPTIMALITY

An intensely interesting and difficult question which potentially impacts all areas of cost modeling is the choice between realism and optimality as the focus for model building. The specific question is, should a particular cost model (or element) attempt to model the costs which will actually occur or should it model an "optimal" process?*

To illustrate the difference, consider spare stockage estimation. Most cost models of which we are aware (except those using fixed proportions of acquisition cost) base spares estimates on an optimization routine that buys enough to fill up a pipeline and provide a buffer stock whose size is related to the theoretical

* Such terms should be used cautiously. We mean quasi-optimal or as close to optimal as feasible, given constraints on model size, running time and so on.

variance of the failure distribution and the desired confidence-against-stockout.* This is an optimal system.

The alternative would recognize that spares will normally not be purchased at optimal levels. The exigencies of budgeting dictate that systems will frequently be deployed with less than the optimal level of spares. Even if they were optimally spared, the (real) non-stationarity of failure rates will mean that, initially, spares complements will be insufficient because of burn-in problems.

In the Navy, the initial lack of sufficient spares characterizing deployment of most systems has had frequently disastrous effects which arise from behavioral responses to inadequate supply. For example, a maintenance technician may attempt an unauthorized repair. This can increase the failure rate if, as expected, he does further damage, and increase the demand lead time by delaying entry of the part into the established repair cycle. After being ill-served by the repair system (which usually requires a year or two to become as effective as predicted), the technician will begin doing things such as ordering components he doesn't need and refusing to turn in faulty components until a replacement is available. These modes of behaviour raise demand rates and increase

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* A few models operate from a budget constraint and achieve as high a confidence level as possible. Also, while related, a number of criteria are used: NORS rates, backorder rates and availability rates are examples. All such models share the fundamental characteristic under discussion: they attempt to optimize spares levels given either budget or effectiveness constraints.

lead times. The net affect is that, over the life of the system, a great many more spares will be required than the original optimal number, because the support environment will have changed.

The reader will recognize that to model the reality is far more difficult than to model a theoretical or optimal structure. This is one, very important, argument against modeling reality, no matter what the circumstances.

The cost of doing so notwithstanding, there may be other reasons to stick with optimal structures in lieu of reality. One way to decide would seem to be a consideration of what we expect these models to do for us. To address that issue requires us to make a distinction between cost estimation and cost analysis.

Every cost model produces estimates of cost. Very few models, however, are intended for use as tools of analysis: tools which support decision-making by clarifying the relative cost implications of different decisions. To be useful as tools of analysis, models must be easy to use and responsive to the variables over which the user has control. For example, a designer needs a model that is responsive to failure rates since he can alter them, but not one that is responsive to the number of systems purchased since only his customer can influence that variable (although it is usually convenient for him to understand how quantity effects things).

It is basic to the HARDMAN approach that the most critical decisions are the earliest ones. It follows that tools of analysis are most important in the early stages of development. It is also fundamental that accurate planning be done early enough to provide a basis for real resource allocation decisions. The timing of the Weapons System Acquisition Process is usually such that most detailed allocation decisions can wait until close to the end of full scale development and the beginning of production. The implications of these remarks are that Level I models should be good tools of analysis while Level III models should provide very reliable cost estimates.

Optimal structures, because they are simpler, are most appropriate for use in tools of analysis. By modification, especially through addition of empirically determined cost estimating relationships to the basic structure, models formulated in this way can also provide reasonably accurate estimates.

But cost estimates used to develop detailed plans and specifications for the support apparatus should be far more accurate than those obtainable with optimal structures. Therefore, estimation of costs in the later stages of development should be based, as much as possible on reality.

The problem with adopting these recommendations as the basis for developing models is that, where real structural differences arise, this may tend to violate the mathematical linkage requirement discussed in Section 2. The resolution of this problem may lie in the use of parametric relationships to bridge the gap between reality and optimality. This is another research question which will have to await the actual development and testing of a complete model system (all three levels) which has not, as yet, been done.

4.0 CONCLUSIONS AND RECOMMENDATIONS

As the foregoing discussion indicates, some issues appear to be far more settled than others. In almost all cases we have reached definite conclusions, whether some question remains or not. Where there is a reasonable degree of uncertainty, the recommended course of action reflects this. Each issue is taken separately, the conclusion stated as succinctly as possible, followed by the recommended course of action.

Linked and Graded Model Systems

The research has shown that linked and graded systems are feasible. The use of Level I systems by several design teams indicates the acceptability and utility of the only element in these systems not in common use.

> Recommendation: that HARDMAN adopt the three level Linked and Graded model system structure for implementation of cost methods.

Modularity of Cost Models

Development of the HARDMAN models in the variety required to serve the WSAP can be most effectively carried out with a modular approach where modules are cost elements or groups of cost elements. The extra costs and risks associated with presentation of the models in a modular form outweigh the costs associated with providing the appearance of special purpose models to the users.

Recommendation: that HARDMAN adopt a modular approach to the development of cost models but provide them to users as special purpose models.

Manpower Formulations

While the algorithms developed for early manning estimates have desirable characteristics, there is a considerable question about the feasibility of providing data to drive them. Nonetheless, the distinction between compensation costs depending on hour-by-hour opportunity cost of labor, and training and other cost elements dependent upon integer numbers is an important contribution to cost realism.

Recommendation: that, initially, manning algorithms be based on those developed in the DMS to determine the severity of data acquisition problems and to alter the algorithms as necessary while retaining the essential structure.

Spare Stockage Formulation

Level I and II spares algorithms developed in the DMS provide more accurate simulation of simultaneous process formulations than any others available for use in sequential processing models.

Recommendation: that HARDMAN adopt the spares cost estimation techniques developed in the DMS.

Reality Versus Optimality

Level I models should be developed primarily as tools of analysis and only secondarily as accurate cost estimating devices. Level III models should be as accurate as possible though still capable of use in cost analysis. Optimal structures are appropriate for tools of analysis while realistic models provide better estimation. Parametric relationships may provide a means for reestablishing linkage destroyed by the use of these two dissimilar approaches.

> Recommendation: that Level I models be based on optimal structures, emphasizing their use as tools of analysis and Level III models be made as realistic as possible and that cost estimating relationships be explored as a means of preserving linkage between the model levels.